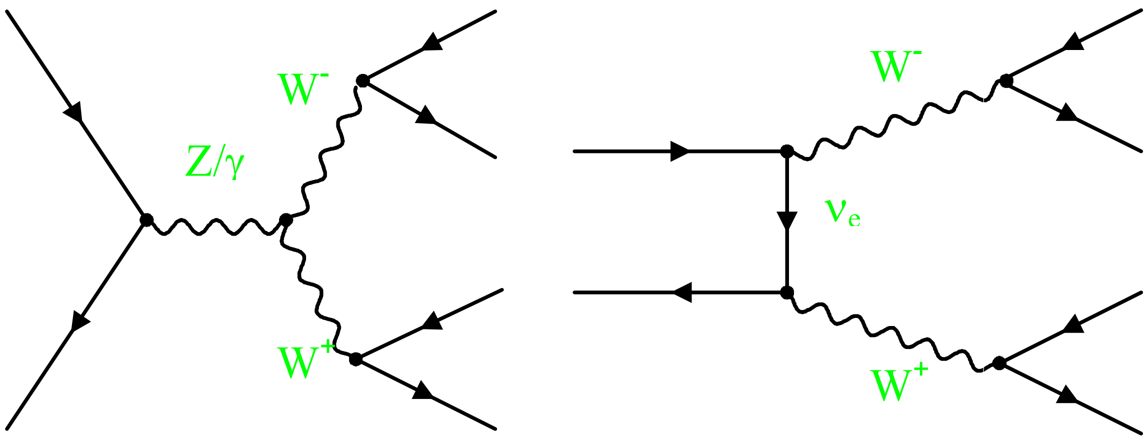
W mass and W^+W^- final state interactions

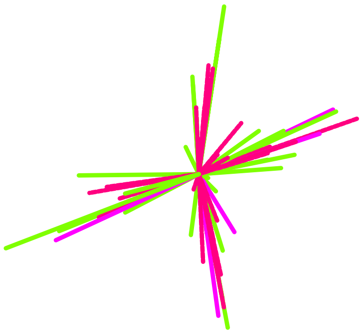


Nigel Watson
University of Birmingham

Outline

- W mass and width
  - ⇒ systematics
- Colour Reconnection
- Bose-Einstein Correlations
- Combined LEP Results
- Summary

W^+W^- final states



BR=45%

~ 87% efficiency

~ 20% impurity, mostly $Z \to$qqgg

4 jets, fully observed

☹ jet-jet ⇔ W ambiguity

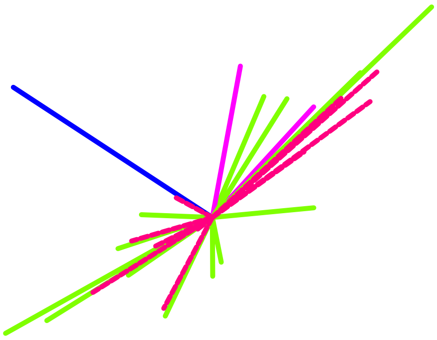
☹ Final State Interactions

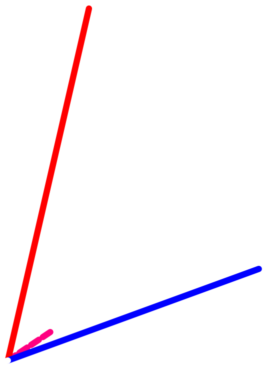
BR=44%

~ 85% efficiency

~ 10% impurity, mostly non-WW 4-f

2 jets, 1 charged lepton, $\geq 1\ \nu$





BR=11%

~ 80% efficiency

~ 10% impurity, mostly non-WW 4-f

☹ 2 charged leptons, $\geq 2\ \nu$

minimal impact on M_W.

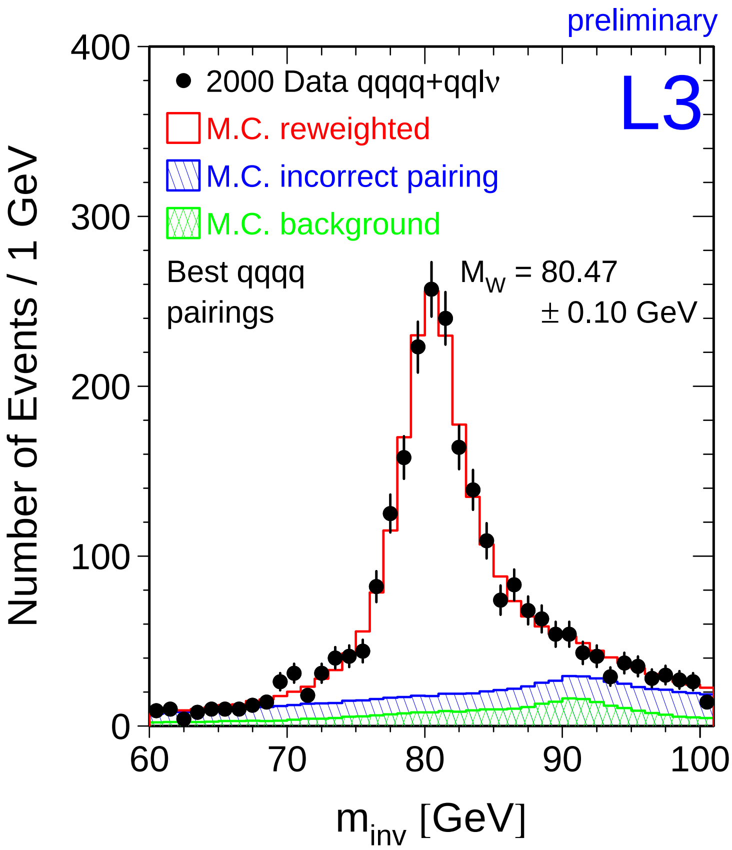
ADLO combined, ~ 2 300 pb^{-1} data for M_W measurement

$\Rightarrow$ 30 000 W^+W^-

82% all LEP2 sample analysed (100% Aleph, L3)

Invariant Mass Reconstruction

Reconstruct jets (q, g) and charged leptons



Constraints

4 sum (E, p) = (√s, 0)

1 mass W^+ = mass W^-

Jet energy measurement

poor cf. angles

Kinematic fit → improved mass resolution

qqlν 1C, 2C fits for l=e,μ

1C only for l=τ (τ energy unknown)

qqqq 4C, 5C fits 2 or 1 masses/event

Choose/weight jet pairing by: di-jet angles,

kin. fit probability, masses, CC03 matrix element

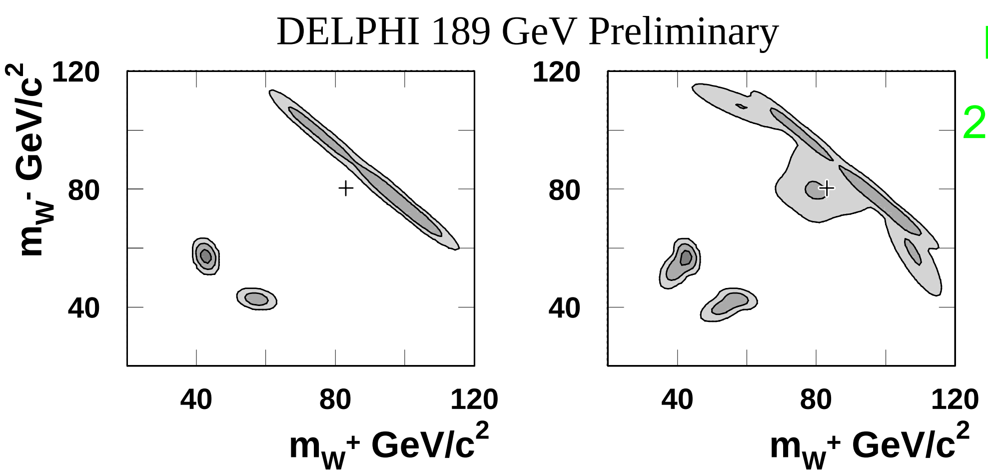
M_W Determination

3 methods

- Reweight "detector level" MC to arbitrary M_W [A,L,O]
  - 1d fit to average mass, ≥1 bins of mass error
  - 2d fit to 4C fit mass
  - implicit MC correction

- Direct analytic fit [O]
  - Asymmetric Breit-Wigner, explicit MC calibration

- Convolve Breit-Wigner with resolution, ISR [D,O]
  - $L(M_W, m_{rec}) = p_w.BW(M_W, m, s') \otimes ISR(s, s') \otimes R(m, m_{rec})$
  - 1d or 2d



Reconstructed 2d p.d.f. for MC qqqq event

Systematic Effects

Important! > **combined statistical** error = 26 MeV

Errors either uncorrelated, or correlated:

— between expts. and channels

— between expts. in single channel

	Uncertainty on M_W (MeV)		
Source	**qqlν**	**qqqq**	**Combined**
ISR/FSR	8	8	7
Hadronisation	19	17	18
Detector	11	8	10
Beam energy	17	17	17
Colour Reconnection	-	40	11
Bose-Einstein	-	25	7
Other	4	5	3
Total systematic	**29**	**54**	**30**
Statistical	**33**	**31**	**26**
Total	**44**	**63**	**40**

- BEC/CR uncertainty ⇒ qqqq net weight = 0.27
- With equal systematics, statistical uncertainty = 22 MeV

ISR/FSR

- Compare ISR models, e.g. in KORALW/EXCALIBUR
- Reweight KORALW (LLA) $O(\alpha^3) \rightarrow O(\alpha^2)$, $O(\alpha^1)$

  – incomplete at $O(\alpha)$, no ISR↔FSR, W+γ

  $\Longrightarrow$ Full $O(\alpha)$, DPA of RACOONWW (unweighted)

Hadronisation

- Compare various models and parameter variation
- Reweight relevant variables MC/data, propagate $\rightarrow M_W$
- Mixed Lorentz Boosted Z^0 (MLBZ) (D)

Beam Energy

$\Delta M_W = M_W \,.\, \Delta E_{beam} / E_{beam}$

- Resonant depolarisation, NMR probes/flux loop
- LEP Spectrometer

Final State Interactions

- Colour Reconnection (QCD vacuum properties)
- Bose-Einstein Correl$^{n.}$ (coherent particle production)

Colour Reconnection

Two colour singlets, may not hadronise independently

W^+W^- decay vertices ~ 0.1 fm
hadronic scale ~ 1 fm
} large spacetime overlap

Perturbative CR suppressed ~ $(\alpha_s/\pi)^2\Gamma_W/N_c^2$

Non- perturbative CR, implemented in hadronisation models

- More reconnection (+background!) when hadronisation regions overlap
- spacetime picture of shower development important

"Observable" Effects

- Inclusive multiplicity, $\ln(1/x_p)$, soft or heavy particles
- Particle distribution relative to 4-jet topology
- Aim to control/calibrate systematic on M_W

Analysis Method

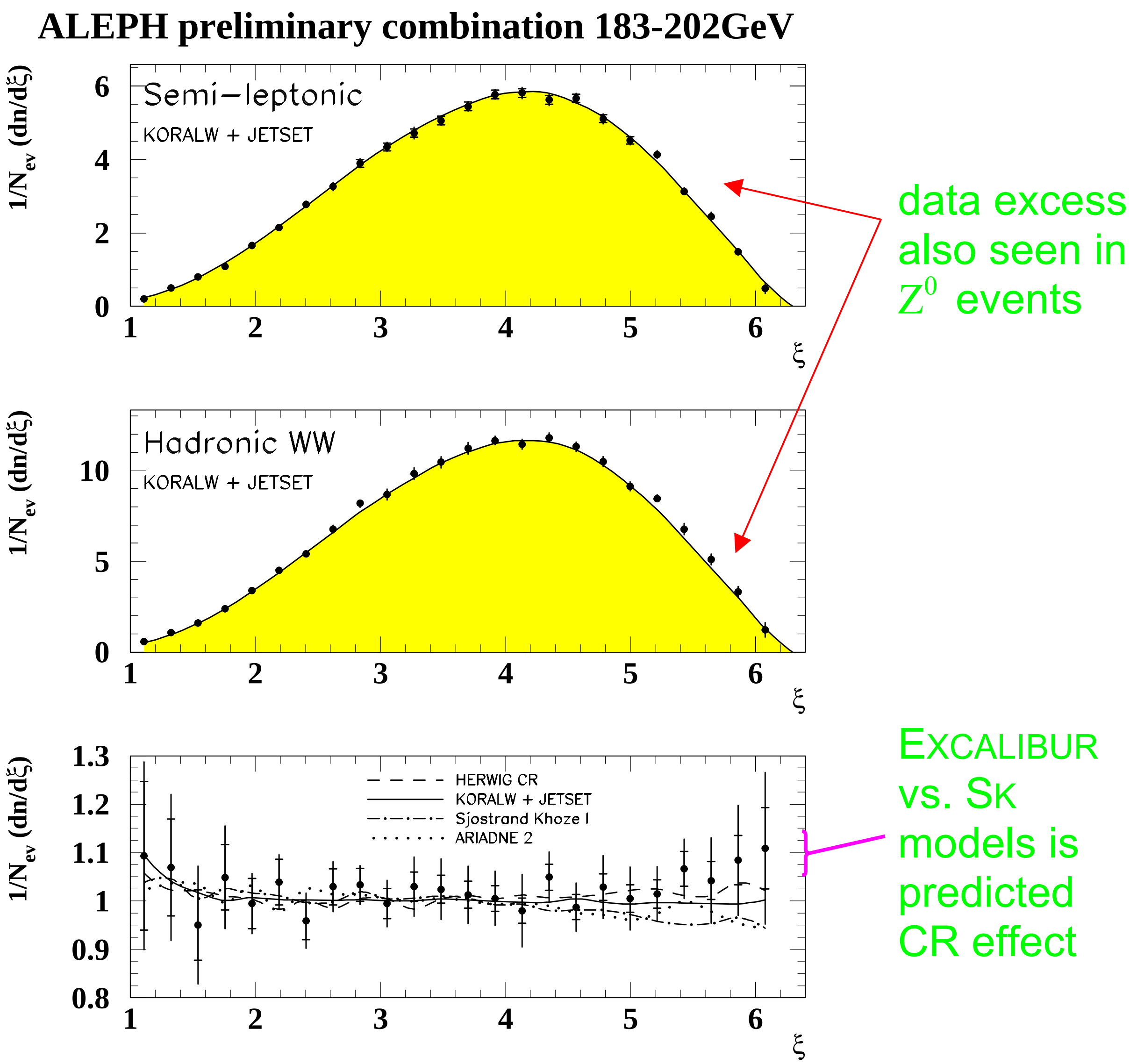
- Compare qqqq data with: models, no-CR and CR
  MLBZ or qqlν data

Inclusive Analyses

CR effects expected larger for soft particles, $p<\Gamma_W$

Look at observables with implicit scale, e.g. $\ln(1/x_p)$, p_T, y

$\ln(1/x_p)$



Uncorrected data, ratio 4q/qqlν not expected flat

Data consistent with CR and non-CR models

Integrate to obtain $\langle n_{ch} \rangle$

Charged Particle Multiplicity

Compilation of (mostly) preliminary results

Define $\Delta\langle n\rangle = \langle n^{4q}\rangle - 2\langle n^{qql\nu}\rangle$

All errors are stat.⊕syst.

Expt.	$\langle n^{4q}\rangle$	$\langle n^{qql\nu}\rangle$	$\Delta\langle n\rangle$
ALEPH* 183–202 GeV	35.75±0.54	17.41±0.19	+0.98±0.43#
DELPHI 183 GeV	38.11±0.72	19.78±0.65	See below
189 GeV	39.12±0.49	19.49±0.41	
L3 183–202 GeV	37.90±0.43	19.09±0.24	−0.29±0.40
OPAL 183 GeV	39.4±0.8	19.3±0.4	+0.7±1.0
189 GeV	38.31±0.44	19.23±0.27	−0.15±0.58

∗ Not corrected for selection, # is $\Delta\langle n\rangle$(data) - $\Delta\langle n\rangle$(MC)

DELPHI measure [Eur.Phys.J.C18(2000)203]

$\langle n^{4q}\rangle / 2\langle n^{qql\nu}\rangle = 0.981 \pm 0.027$ $0.1<p<1$ GeV

All models except ARIADNE 3, VNI consistent with data

Similarly for particle dispersion

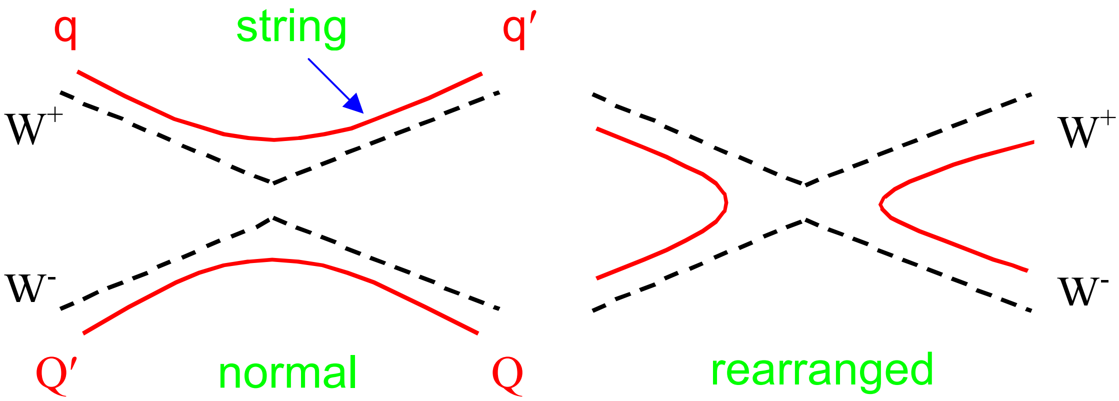
Systematic > statistical uncertaainty

⇒ combination requires proper treatment of correlations

“Heavy hadrons”, numerically larger effects, less sensitive

Interjet Analysis (L3)

Motivated by simple string picture of reconnection



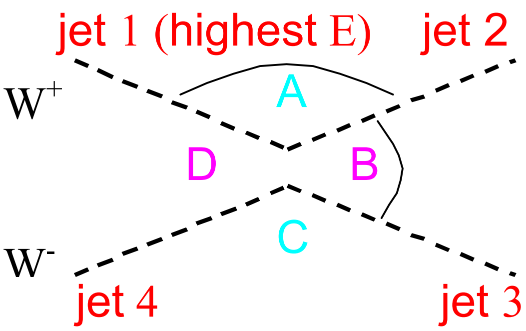
Non-standard qqqq selection, plus topological cuts:

2 larger jet-jet angles $100^0 < A,C < 140^0$, +not adjacent

4 distinct jets

$y_{34} > 0.01$

($k_\perp$ scheme)

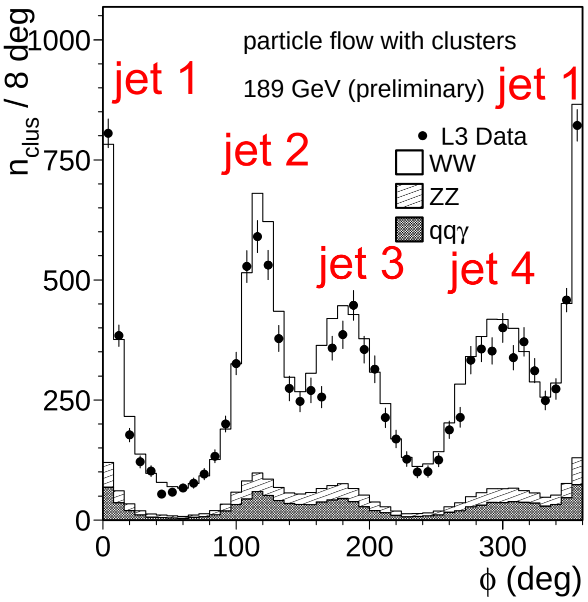


2 smaller jet-jet angles B,D $< 100^0$

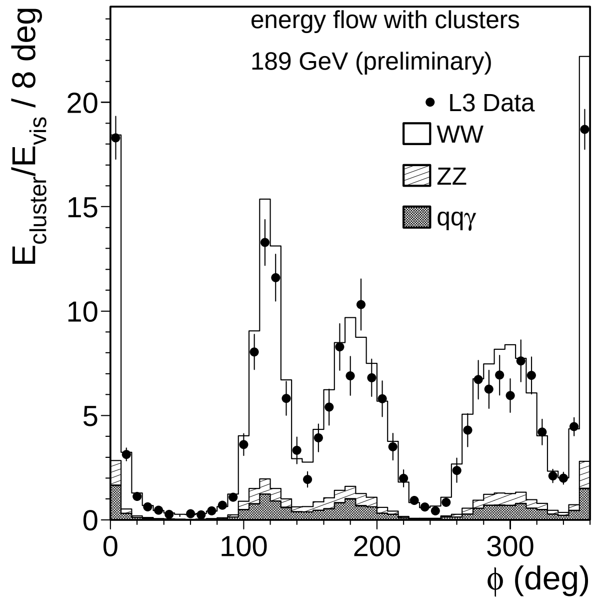
- "strings" back-to-back, not crossing
- good jet-jet $\Leftrightarrow$ W associations, 4 partons similar energy
- $WW \rightarrow$ qqqq, efficiency=15%, purity=85%, 189 GeV MC

  $\Longrightarrow$ 209 candidates at $\sqrt{s} \approx 189$ GeV
- Correct pairing+non-crossing topology in 87% events

- project particles onto jet 1-jet 2 plane
- follows earlier idea, “string effect” for 4-jets

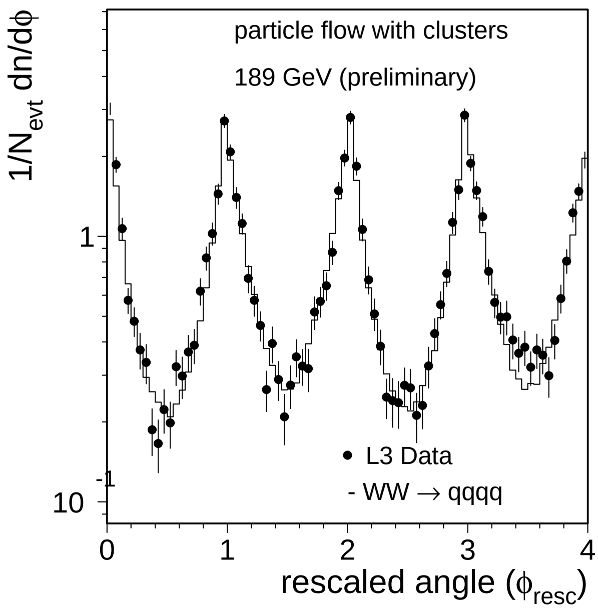


multiplicity flow

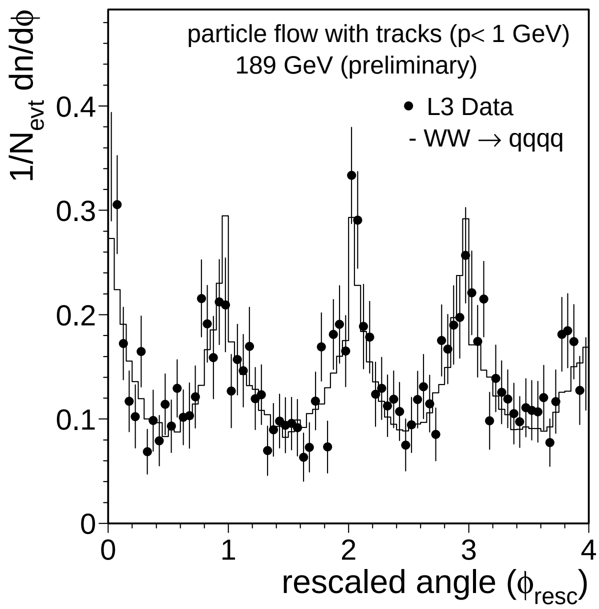


energy flow

- Normalise flow to jet-jet angles, subtract background, correct non-planarity of 4-jets

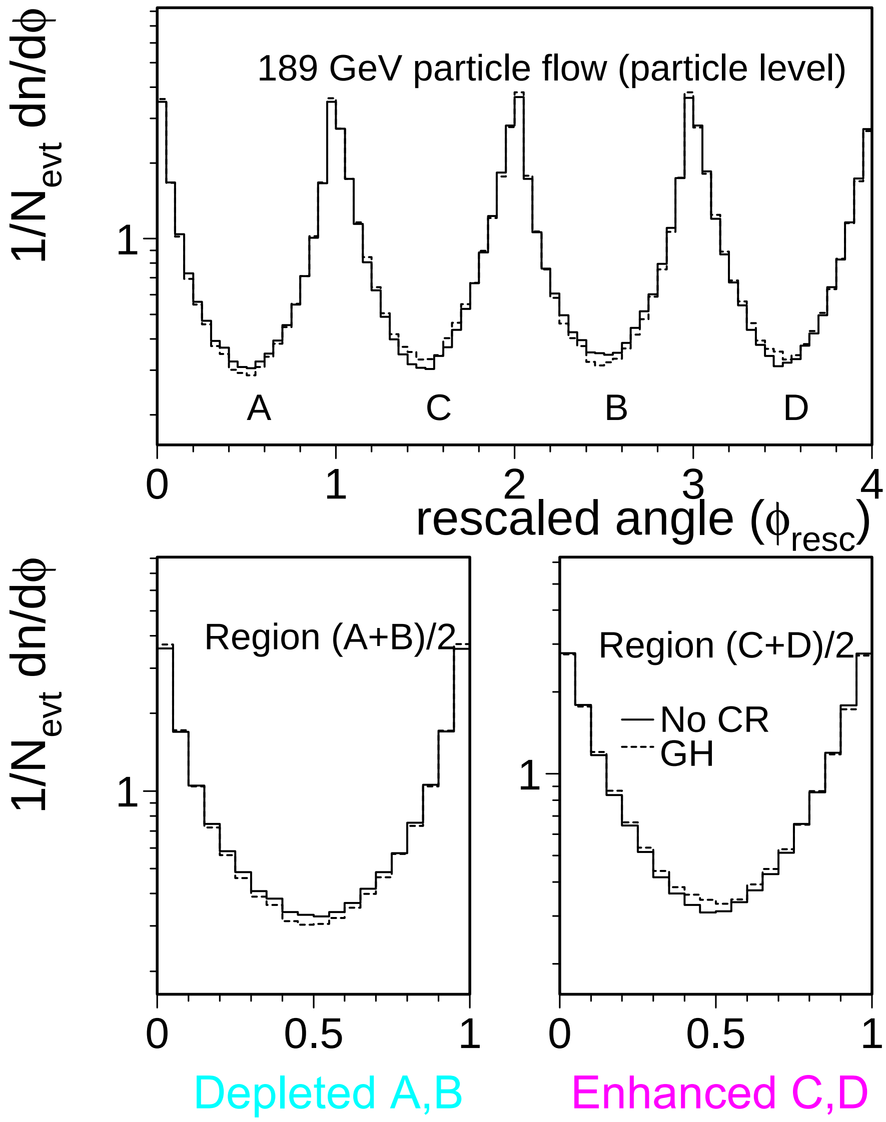


multiplicity flow



energy flow, p<1 GeV

Model study without detector simulation



Predictions for

p>0.1 GeV

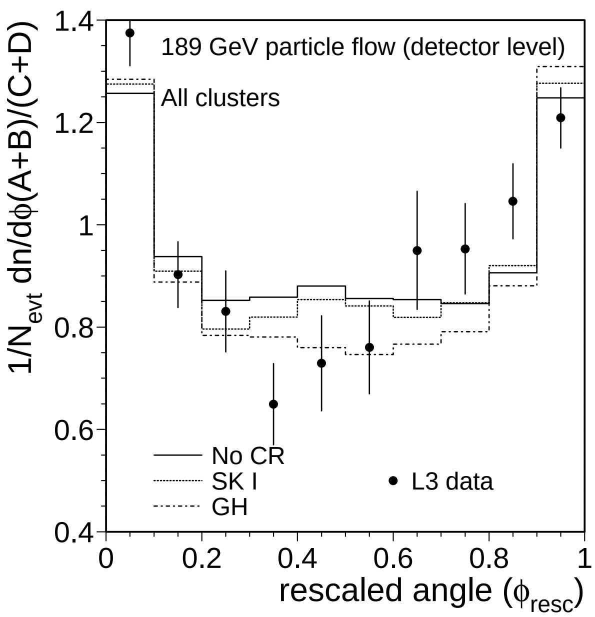
Improved comparison by averaging regions:

- between jets of different Ws (C,D)
- between jets of same W (A, B)

Examine ratio (C+D) / (A+B)

- Quantify $\dfrac{\int dn/d\chi_R \,(\text{inter-W})\, d\chi_R}{\int dn/d\chi_R \,(\text{intra-W})\, d\chi_R}$, $\chi_R = 0.2–0.8$

Reduced angle flow in data



L3 189 GeV.

Sensitivity SK I (100%) = 3.2σ

SK I (32%) ~ 0.5

OPAL 189 GeV.

Looser cuts:

high efficiency 42%

same purity.

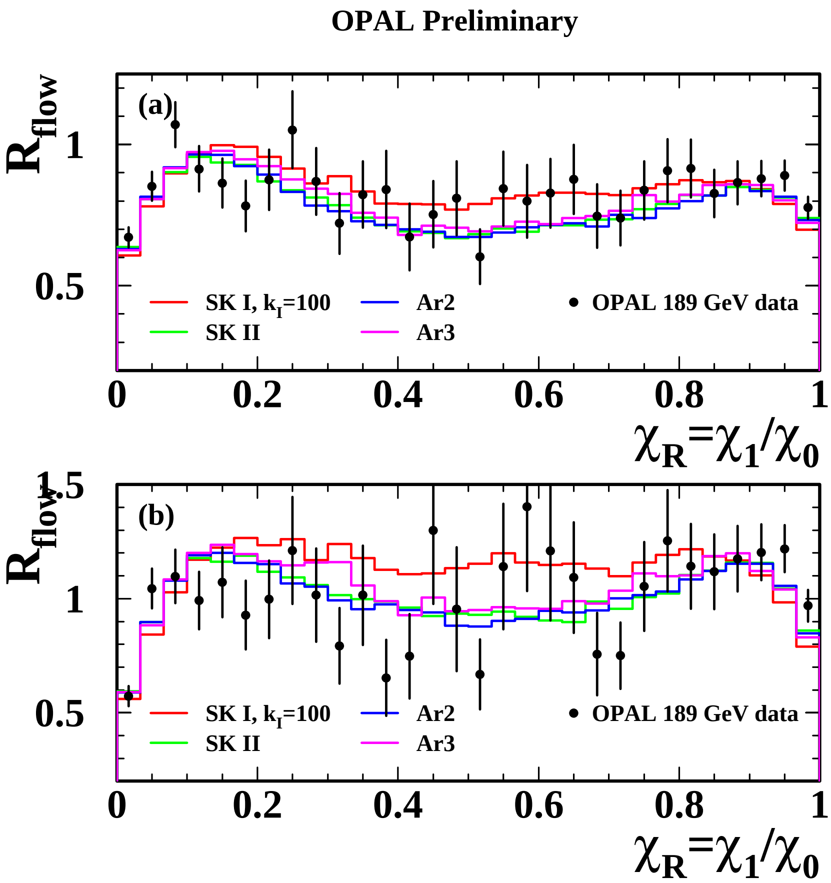
Jet pairing l'hood

Kinematic fit axes

No double counting

Predicted sensitivity

improves slightly

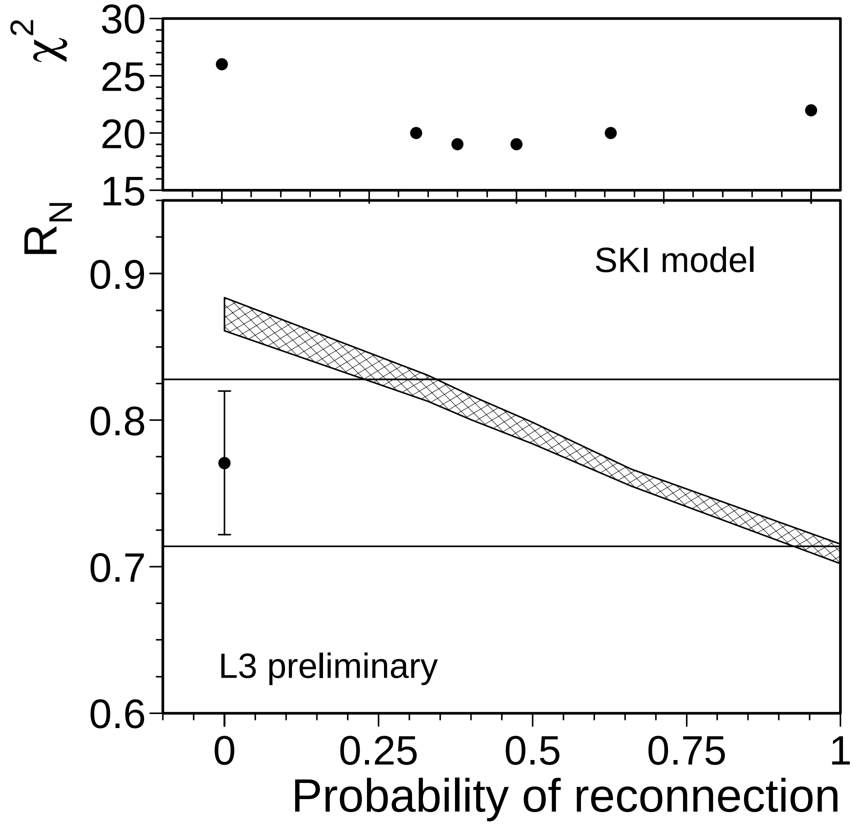


This analysis, favours SK I ~65% reconnected

OPAL repeat of L3 analysis, best agreement with no-CR…

Towards mass biases

Estimate preferred P_{RECON} in models from data



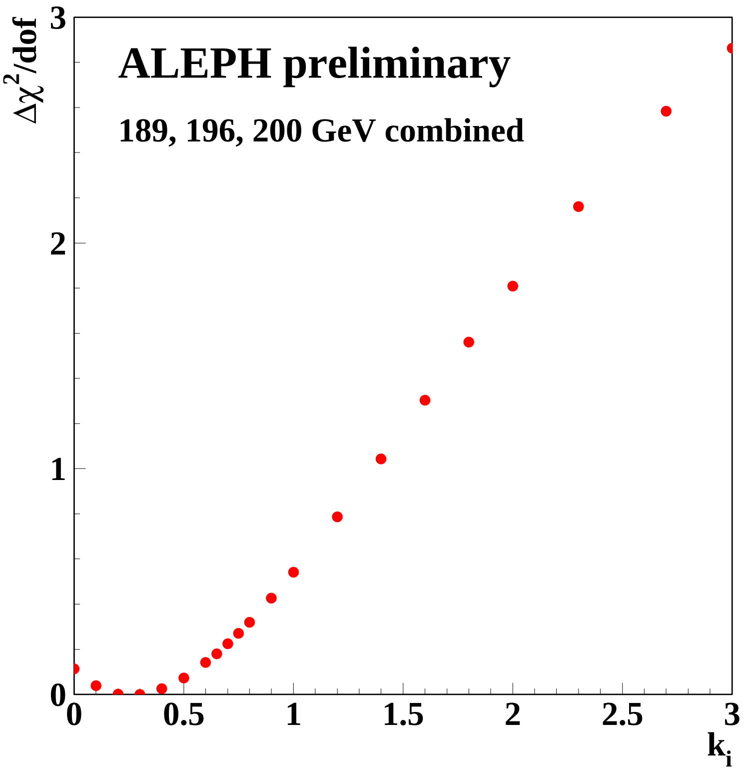
L3 data prefer

SK I prob. ~ 40%

1.7σ from no-CR

ALEPH data prefer

SK I prob. ~ 15%



Non-trivial differences in model predictions A/D/L/O

Bose-Einstein Correlations

Enhanced production of identical boson pairs ($\pi^+\pi^+$ or $\pi^-\pi^-$) at small 4-momentum difference, $Q^2 = -(p_1 - p_2)^2$

Firmly established phenomena, LEP1 and intra-W

Traditionally studied using 2-particle correlation function:

$$R(p_1, p_2) = \rho_2(p_1, p_2) / \rho_0(p_1, p_2)$$

Problem 1

Reference ρ_0 should be identical to ρ, but without BEC, so:

- Unlike-sign data, / ratio of same in MC (resonances)
- Like-sign MC without BEC (MC modelling)
- Event mixing

Many ways to study effect, all experiments differ!

Essential question: do BEC exist between W^+ and W^- ??

Problem 2

non-pQCD amplitudes unknown, resort to models

phenomenological parametrisation $R(Q) \sim 1 + \lambda \exp(-r^2Q^2)$

BE strength (λ)

source radius (r)

OPAL Analysis

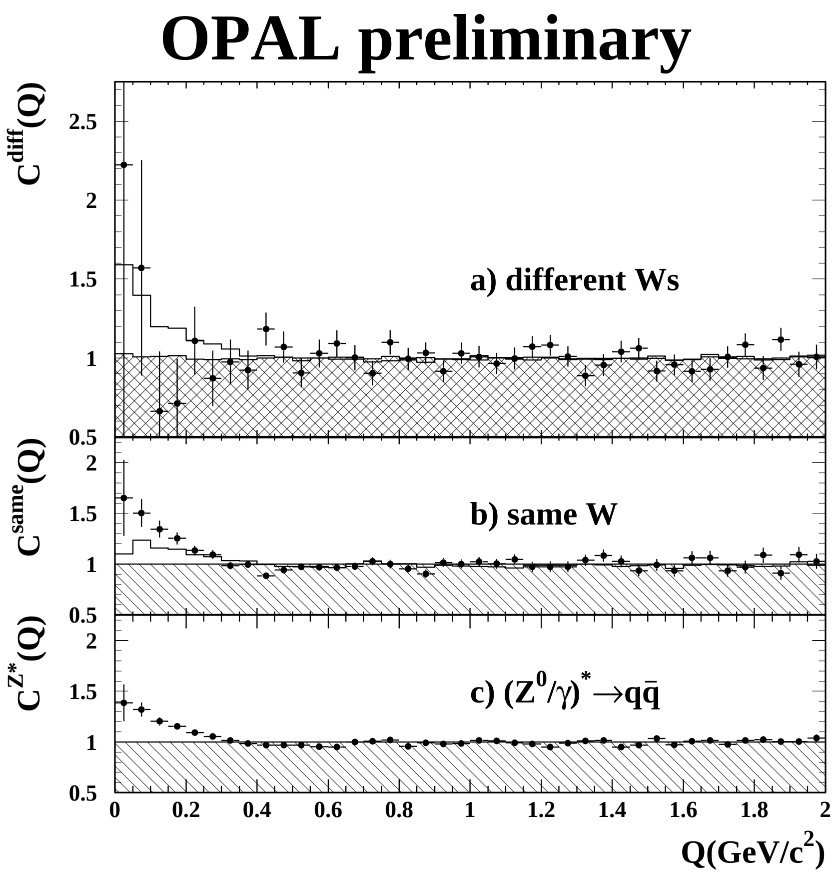
C(Q) ~ ratio (like-sign/unlike-sign) | (data)/(no-BEC MC)

3 event classes: $W^+W^- \rightarrow qqqq$, $W^+W^- \rightarrow qq l\nu$, $Z/\gamma \rightarrow qq$

Each class C(Q) = sum of pure contributions x prob. (MC)

- $C^{DIFF}(Q)$ inter-W BEC
- $C^{SAME}(Q)$ intra-W BEC
- $C^{Z^*}(Q)$ non-radiative qq

} simultaneous fit, extract λ^{DIFF} for various source size hypotheses



e.g.

$R^{DIFF} = R^{SAME} = R^{Z^*}$

$\lambda^{DIFF} = -0.14 \pm 0.36$

$\lambda^{SAME} = 0.70 \pm 0.10$

indep. R's

$\lambda^{DIFF} = 2.9 \pm 1.7$

$\lambda^{SAME} = 0.62 \pm 0.10$

Establishes intra-W BEC

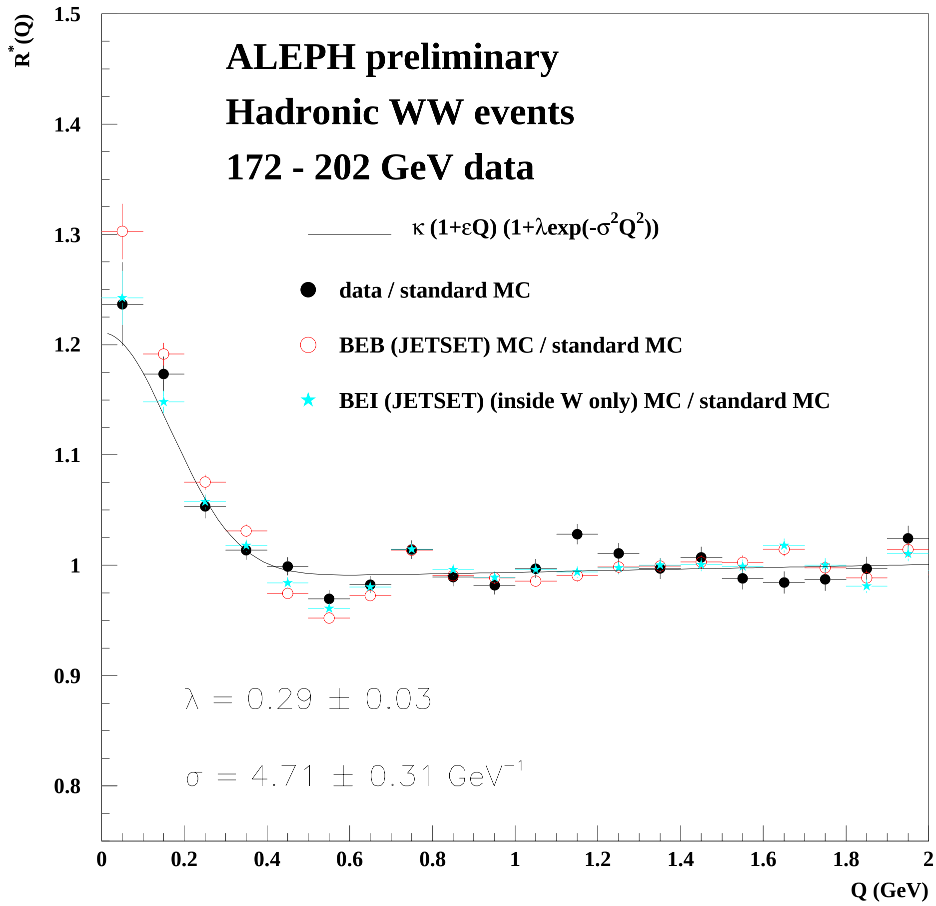
Unable to determine whether inter-W BEC exist

ALEPH Analyses

R(Q) ~ ratio (like-sign/unlike-sign) | (data)/(no-BEC MC)

Include $Z/\gamma \rightarrow qq$ background with BE_3

BE_3 model tuned with high statistics 91 GeV data



Disfavours inter-W BEC at 2.2σ

Compatible with intra-W BEC

Event mixing analysis

Also (qualitatively) disfavours inter-W BEC

L3 Analysis

Idea from Chekanov, De Wolf, Kittel, E.Phys.J.**C6**('99)403

If W^+ and W^- decays uncorrelated

$$\rho_2^{WW}(p_1,p_2) = \underbrace{\rho_2^{W+}(p_1,p_2) + \rho_2^{W-}(p_1,p_2)} + 2\underbrace{\rho_1^{W+}(p_1)\,\rho_1^{W-}(p_2)}$$

Take $\rho_2^{W+} = \rho_2^{W-} = \rho_2^{W}$ — Estimate from qqlν

$\rho_{MIX}^{WW}(p_1,p_2)$ — mix 2 qqlν events, $\Rightarrow$ BEC $\equiv$ 0

Remove background:

$$\rho_2 = 1/(Purity.N_{EVENTS}) \, . \, (dn/dQ - dn_{BACKGROUND}/dQ)$$

All background samples include BEC (BE_{32} model)

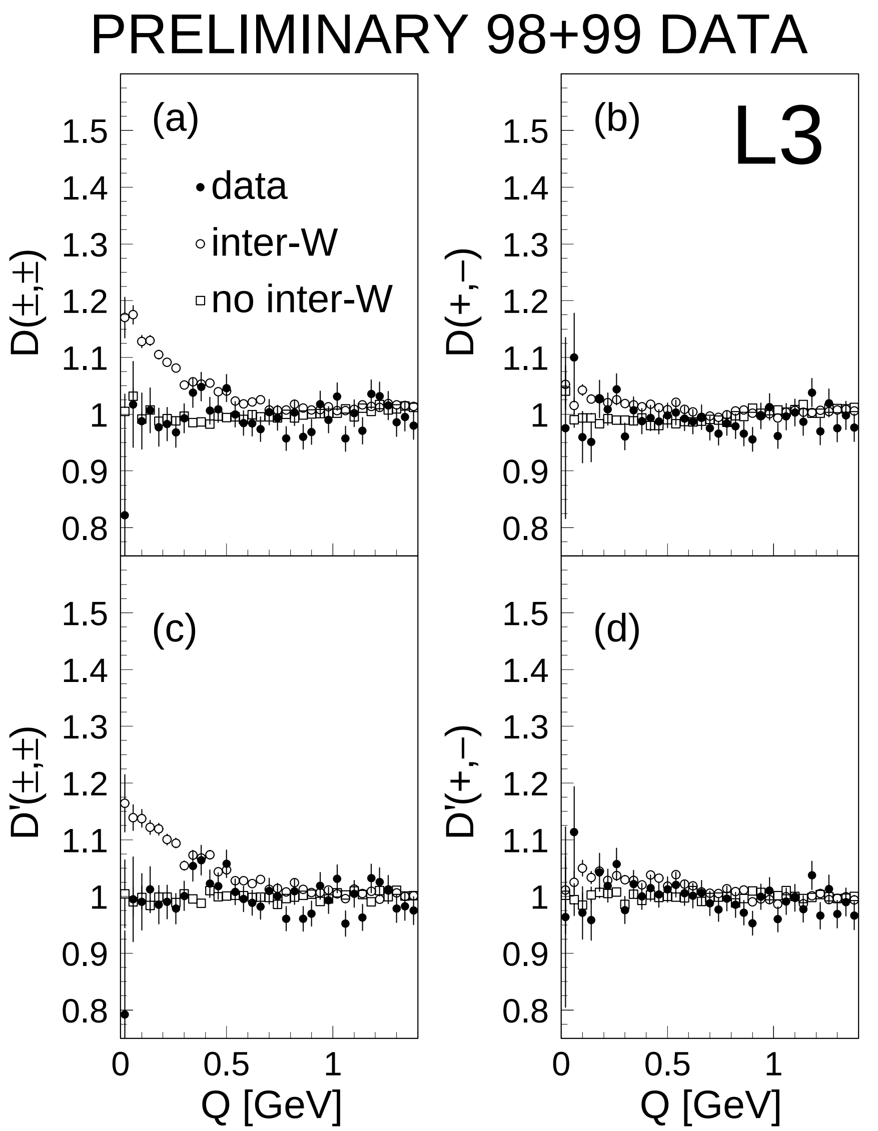
Form ratio D=lhs/rhs

$D' = D(\text{data}) / D(\text{MC, intra-W BEC})$ — remove potential residual bias

$D \cong D' \neq 1$ $\Rightarrow$ non-independent W decays

$\Rightarrow$ plausibly inter-W BEC

Using 1998–1999 data ~60% total L3 luminosity



Single ratio

Double ratio

Data/MC

Fit $D'(Q) = (1 + \varepsilon Q)(1 + \Lambda \exp(-\kappa^2 Q^2))$

No inter-W BEC $\Rightarrow \Lambda = 0$

$\Lambda = 0.013 \pm 0.018$ (stat.) ± 0.015 (syst.)

Compare BE_{32}/Koralw $\Lambda = 0.126 \pm 0.006$ (stat.)

Data disagree with inter-W BEC model by 4.7σ

Preliminary Combined LEP Results

Based on ~ 82% of all LEP2 data

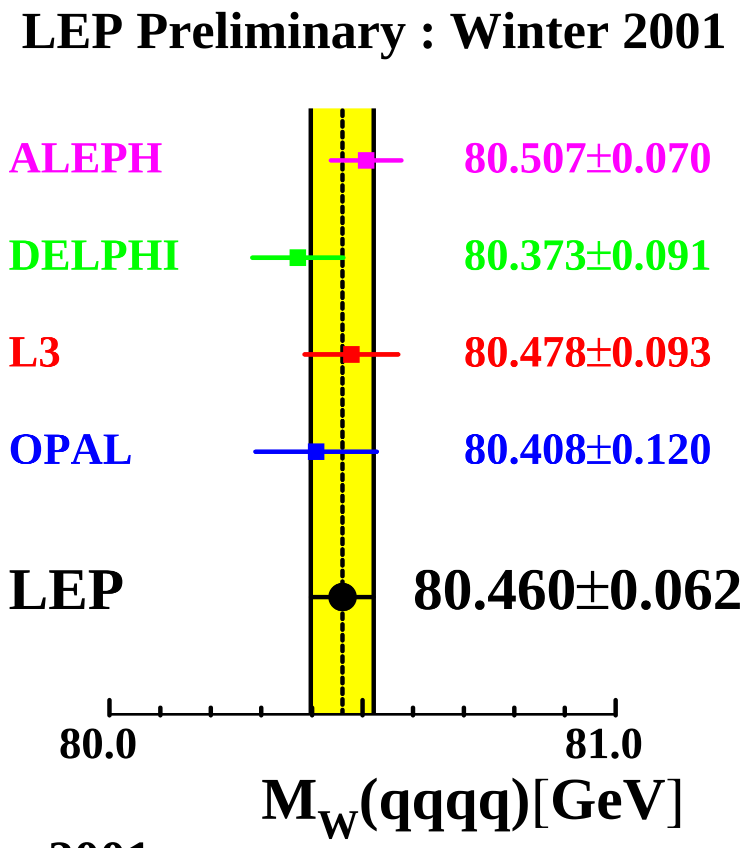
$W^+W^- \rightarrow qqqq$,

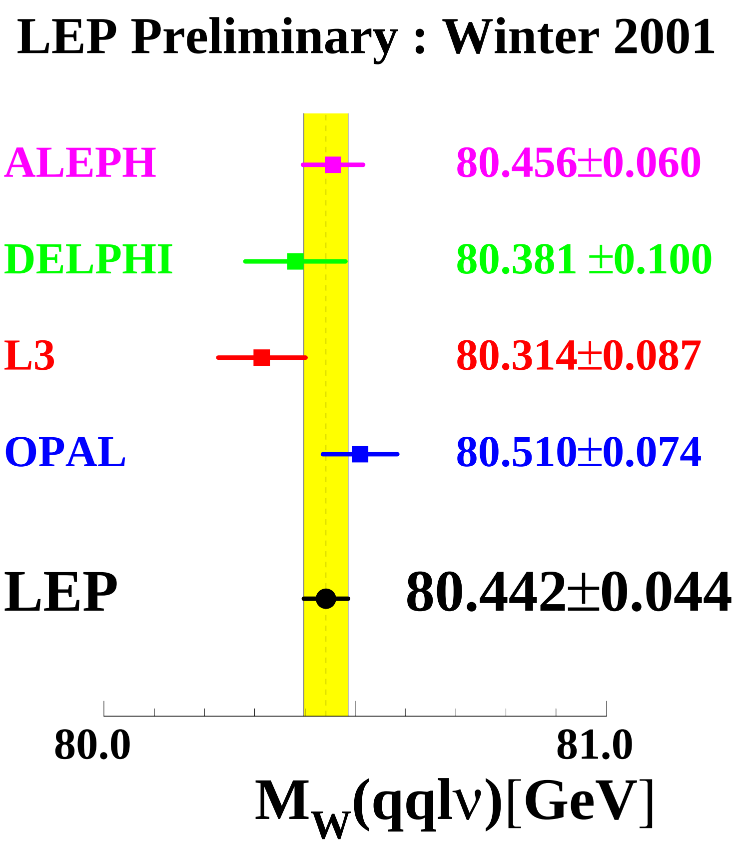
172–208 GeV

χ^2=30.3/32

ΔM_W (stat.)=31 MeV

ΔM_W (syst.)=54 MeV





$W^+W^- \rightarrow qql\nu$

172–208 GeV

χ^2=30.3/32

ΔM_W (stat.)=34 MeV

ΔM_W (syst.)=28 MeV

Preliminary Combined LEP Results

Based on ~ 82% of all LEP2 data

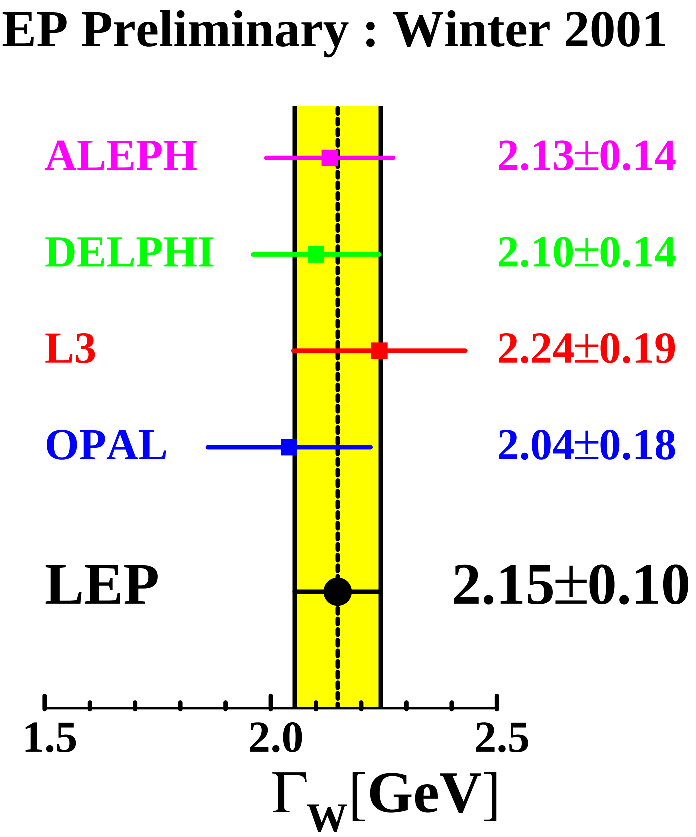
$W^+W^- \to$ qqqq, qqlν

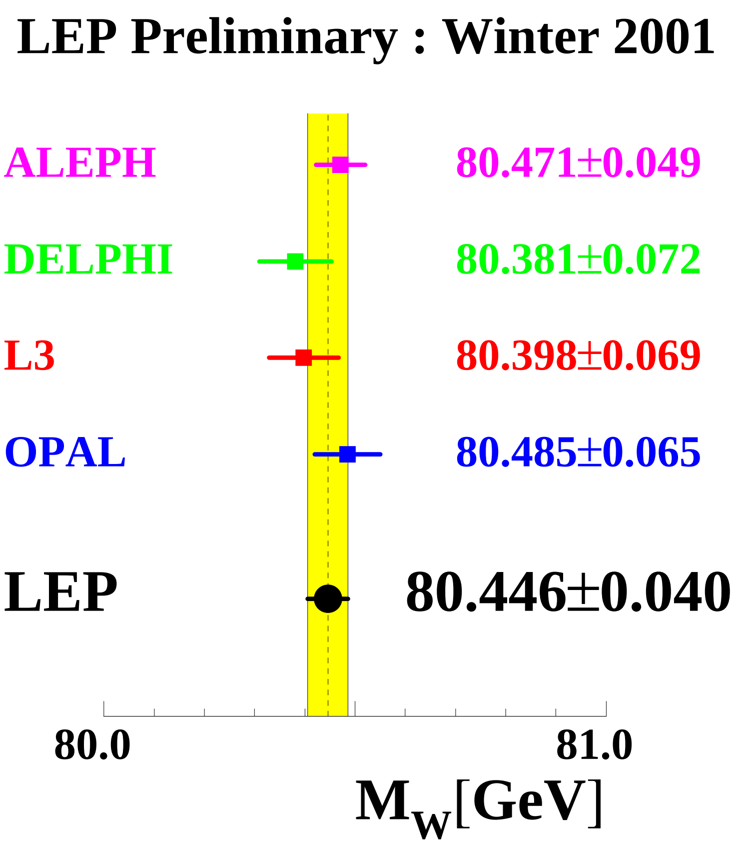
172–208 GeV

χ^2=17.7/21

$\Delta\Gamma_W$ (stat.)=71 MeV

$\Delta\Gamma_W$ (syst.)=63 MeV





$W^+W^- \to$ all

161–208 GeV

χ^2=30.4/33

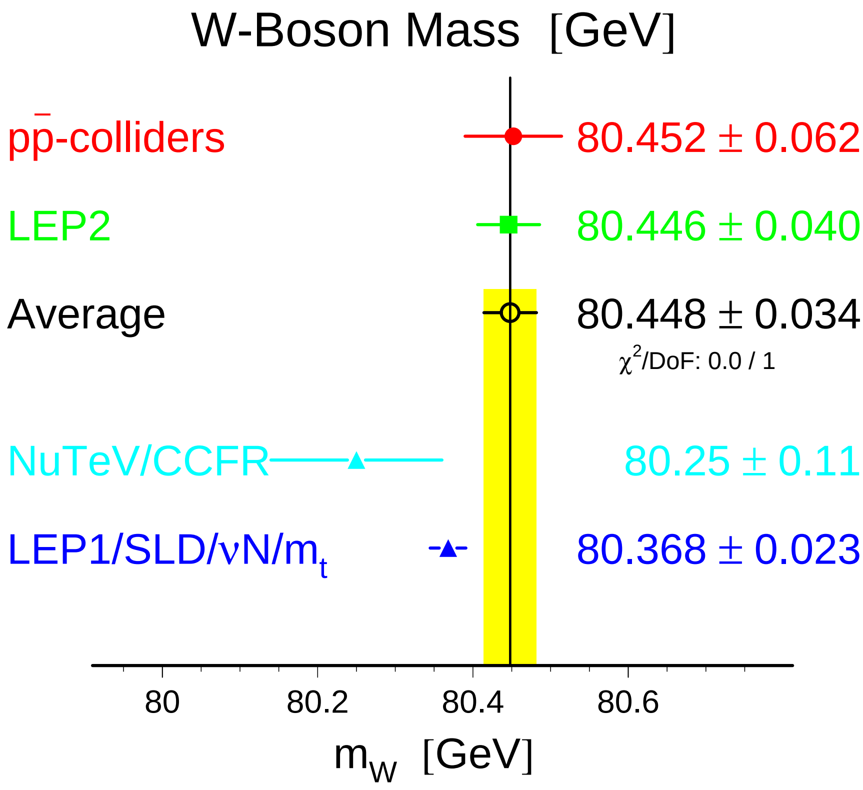
ΔM_W (stat.)=26 MeV

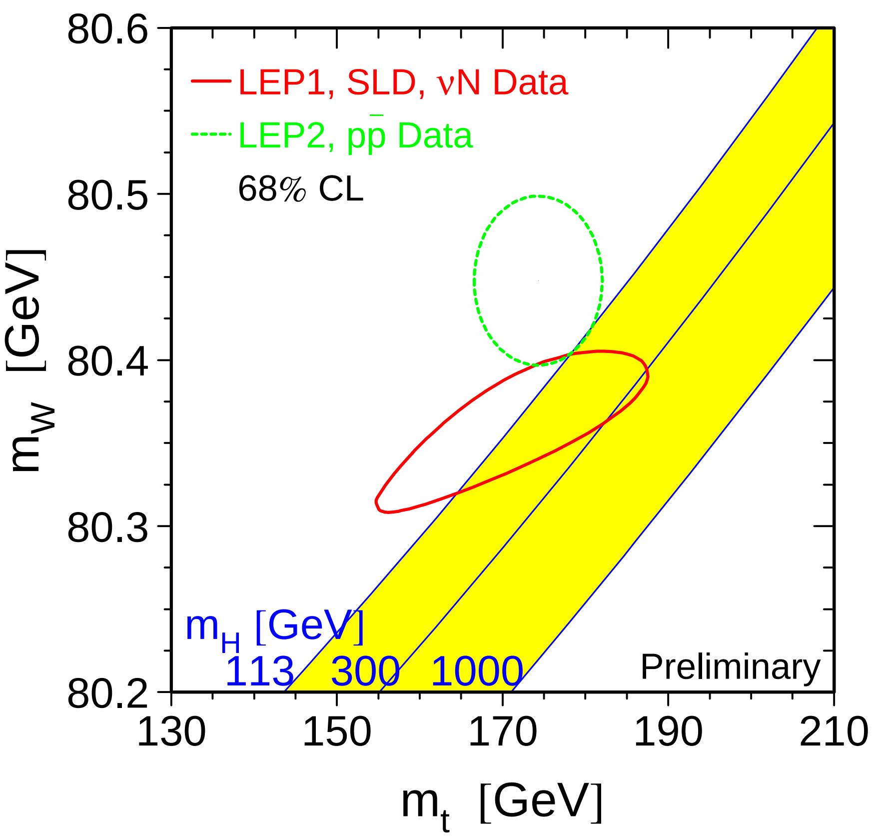
ΔM_W (syst.)=30 MeV

Preliminary Combined LEP Results

LEP M_W currently world best direct measurement.

Use to probe M_{higgs}





Data seem to favour light Higgs

Summary

- 1996–2000, $2.8\,\mathrm{fb}^{-1}$ accumulated, ≈82% used in this M_W

- LEP combined $M_W = 80.446 \pm 0.026 \pm 0.030$ GeV

  [preliminary] $\Gamma_W = 2.148 \pm 0.071 \pm 0.063$ GeV

  $\Delta M_W(qqqq-qql\nu) = +18 \pm 46$ MeV

  – Improved understanding of systematics to come

- Colour Reconnection, must combine results,

  – e.g. interjet multiplicity

  – need to understand model differences among ADLO

- Picture of Bose-Einstein Correlations becoming more coherent at LEP?